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Abstract: We study the dependence of fragmentation in massive gas-rich galaxy disks at z > 1 on stellar feedback schemes and hydrodynamical solvers, employing the GASOLINE2 SPH code and the lagrangian mesh-less code GIZMO in finite mass mode. Non-cosmological galaxy disk runs with the standard delayed-cooling blastwave feedback are compared with runs adopting a new superbubble feedback, which produces winds by modeling the detailed physics of supernova-driven bubbles and leads to efficient self-regulation of star formation. We find that, with blastwave feedback, massive star-forming clumps form in comparable number and with very similar masses in GASOLINE2 and GIZMO. Typical clump masses are in the range 107-108 M , lower than in most previous works, while giant clumps with masses above 109 M are exceedingly rare. By contrast, superbubble feedback does not produce massive star-forming bound clumps as galaxies never undergo a phase of violent disk instability. In this scheme, only sporadic, unbound star-forming overdensities lasting a few tens of Myr can arise, triggered by non-linear perturbations from massive satellite companions. We conclude that there is severe tension between explaining massive star-forming clumps observed at z > 1 primarily as the result of disk fragmentation driven by gravitational instability and the prevailing view of feedback-regulated galaxy formation. The link between disk stability and star formation efficiency should thus be regarded as a key testing ground for galaxy formation theory.

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CLUMPY HIGH-Z GALAXIES AS A TESTBED FOR FEEDBACK-REGULATED GALAXY FORMATION

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ABSTRACT

We study the dependence of fragmentation in massive gas-rich galaxy disks at $z > 1$ on feedback model and hydrodynamical method, employing the GASOLINE2 SPH code and the lagrangian meshless code GIZMO in finite mass mode. We compare non-cosmological galaxy disk runs with standard blastwave supernovae (SN)feedback, which introduces delayed cooling in order to drive winds, and runs with the new superbubble SN feedback, which produces winds naturally by modelling the detailed physics of SN-driven bubbles and leads to efficient self-regulation of star formation. We find that, with blastwave feedback, massive star forming clumps form in comparable number and with very similar masses in GASOLINE2 and GIZMO. The typical masses are in the range $10^7 - 10^8 M_\odot$, lower than in most previous works, while giant clumps with masses above $10^9 M_\odot$ are exceedingly rare. With superbubble feedback, instead, massive bound star forming clumps do not form because galaxies never undergo a phase of violent disk instability. Only sporadic, unbound star forming overdensities lasting only a few tens of Myr can arise that are triggered by perturbations of massive satellite companions. We conclude that there is a severe tension between explaining massive star forming clumps observed at $z > 1$ primarily as the result of disk fragmentation driven by gravitational instability and the prevailing view of feedback-regulated galaxy formation. The link between disk stability and star formation efficiency should thus be regarded as a key testing ground for galaxy formation theory.

1. INTRODUCTION

In the past decade observational evidence has been accumulating that reveals the existence of massive star forming clumps in massive star-forming galaxies at $z > 1$ (Cowie et al. 1995; Elmegreen et al. 2005, 2007; Genzel et al. 2008; Förster Schreiber et al. 2011). The masses and sizes estimated from the observations are large, $10^8 - 10^{10}$ M$_\odot$ and up to a kiloparsec, well in excess of those of present-day Giant Molecular Clouds (GMCs). It has been proposed that such clumps result from the fragmentation of massive gas disks driven by gravitational instability (Noguchi 1998; Agertz et al. 2009; Bournaud et al. 2012). A large body of numerical simulation work has been devoted to study the latter scenario. Early studies, which either neglected feedback or adopted inefficient thermal feedback from SNe, have been producing systematically giant clumps with masses in excess of 10^8 M$_\odot$ within massive gas-rich disks with baryonic masses $> 10^{10}$ M$_\odot$ at $z > 2$. These earlier simulations, however, suffered from overcooling as they were adopting the notoriously inefficient thermal feedback (e.g. Ceverino et al. 2010; Agertz et al. 2009), which artificially enhances both disk instability and star formation. More recently, various works have revisited high-z disk fragmentation, both with cosmological simulations and simulations of isolated disk galaxies, finding less fragmentation even in massive gas-rich disks, and generally lower clump masses, in the range $10^7 - 10^8$ M$_\odot$ (Tamburello et al. 2015; Behrendt et al. 2015; Moody et al. 2014; Mandelker et al. 2015; Oklopcic et al. 2016) , which, at high resolution, show significant substructures (Bournaud et al. 2014; Behrendt et al. 2015). Yet several differences remain among the various published simulations. These are due to a combination of different initial conditions and/or different properties of simulated galaxies, different star formation and feedback recipes, but also potentially different underlying hydro methods and procedures to identify clumps. It has also been highlighted how some of the most massive observed star forming clumps perhaps do not result from "in-situ" disk fragmentation, rather they could be accreted cores of massive satellites (Mandelker et al. 2015; Oklopcic et al. 2016).

Even the recent simulations employ feedback models that overproduce stellar masses at high redshift by factors of a few relative to abundance matching constraints, as highlighted by Mandelker et al. (2015), suggesting that gas may still cool too efficiently. Since disk fragmentation depends on net cooling efficiency (Gammie 2001) it follows that fragmentation might still be overestimated.

An exception is Oklopcic et al. (2016), who uses the FIRE simulations with multiple stellar feedback processes calibrated to reproduce the stellar-to-halo mass relation from low to high redshift (Hopkins et al. 2014), but study in depth only one simulated galaxy making it difficult to generalize their results on the clump properties. The following question thus arises; is widespread disk fragmentation into massive clumps still going to happen in the presence of a feedback model capable of truly regulating dissipation and star formation?

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Furthermore, it is unclear how disk fragmentation depends on the treatment of the hydrodynamics. For protoplanetary disks simulations have shown that fragmentation can be poorly captured by cartesian grid-based AMR codes (Mayer & Gawryszczak 2008), a technique widely used in high-z clumpy galaxy studies (e.g. Bournaud et al. 2011; Ceverino et al. 2010), unless the initial grid resolution is sufficiently high. Likewise, SPH, even in its modern incarnations, may suffer from viscous dissipation and discreteness noise (Durisen et al. 2007)

In this Letter we compare systematically simulations with an "old generation" and a "new generation" stronger feedback model designed to regulate efficiently star formation, the so called "superbubble" SN feedback (Keller et al. 2015) . Moreover, we compare results of GASOLINE2 with equivalent simulations carried out with the new lagrangian mesh-less code GIZMO using the same sub-grid model for star formation and feedback.

2. INITIAL CONDITIONS AND SIMULATIONS

Since the purpose of our study is to scrutinize the dependence of massive galactic disk fragmentation on hydro technique and sub-grid feedback prescription we opt to focus on controlled numerical experiments. Therefore we carry out a set of isolated galaxy simulations. Disk models are constructed as multi-component systems using the standard Hernquist prescription, as detailed in Tamburello et al. (2015). They comprise an exponential disk of stars and gas embedded in an NFW halo, and include adiabatic contraction. We adopt two models of very massive high-z disks, designed to yield most favourable conditions for disk fragmentation. The first model, the default in this work, is the most massive and most gas-rich model adopted in Tamburello et al. (2015), Model 11. This has a disk of mass $\sim 8 \times 10^{10}$ M$_\odot$ with gas fraction of 50%, and is embedded in halo of mass 2.5×10^{12} M$_\odot$. The resulting stellar mass of $\sim 4 \times 10^{10}$ M$_\odot$ is high but still within the limits allowed by abundance matching constraints. The gas temperature is set initially to $\sim 10^4$ K. The peak circular velocity, 350 km/s, is at the very extreme of the line-width of observed $z > 1$ massive star forming galaxies (Wisnioski et al. 2015). We also construct a second disk model that has the same total disk mass and halo mass but a disk gas fraction of 80%, at the upper limit of the values inferred from observations at $z > 1$. The initial conditions (ICs) are relaxed adiabatically to avoid numerical transients which could artificially trigger fragmentation (see Tamburello et al. 2015).

3. HYDRO CODES AND SUB-GRID FEEDBACK

We use the GASOLINE2 and GIZMO hydro codes. GASOLINE2 is an evolution of the GASOLINE SPH code (Wadsley et al. 2004) which includes an alternative formulation of the hydro force using geometric density average (GDSPH), a thermal diffusion term in the energy equation and a Wendland kernel which altogether allow accurate pressure gradient estimates, eliminate artificial surface tension and allow mixing, thus overcoming traditional limitations of SPH (Keller et al. 2014). As in Tamburello et al. (2015) we use a pressure floor to avoid spurious fragmentation. We include non-equilibrium radiative cooling (Shen et al. 2010). A companion run with the "vanilla SPH' used in the original GASOLINE code is also presented for comparison. In addition to adopting standard density-energy hydro force formulation and no diffusion the GASOLINE run adopts a spline kernel (Wadsley et al. 2004). In the GASOLINE2/GASOLINE runs we adopt a fixed gravitational softening of 100 pc and a gas mass resolution of 2.26×10^5 M$_\odot$, which yields hydro resolution as high as 10-20 pc in the high density regions (a run with ten times better resolution was presented in Tamburello et al. (2015) yielding similar results).

GIZMO is a mesh-free lagrangian code based on discrete particle tracers that partition the volume as unstructured cells using a kernel function as in SPH (Hopkins 2015). However, unlike SPH codes, these tracers only represent a volume partition, sharing an "effective face" with the neighbouring ones. The Riemann problem is then solved across these faces, as mesh-based codes, allowing excellent shock capturing properties and detection of discontinuities as in finite volume grid-based codes. The unstructured cells are not fixed in space and time, resulting in a Lagrangian nature of the scheme which allows for intrinsic adaptive resolution and an almost exact conservation of angular momentum (up to gradient errors; Hopkins 2015). Gravity is based on the tree algorithm inherited from GADGET3, descendant of GADGET2 (Springel 2005), which guarantees high accuracy as well as fast computation. We use a cubic spline kernel function in GIZMO, and the corresponding force softening kernel function (Hopkins 2015). The gravitational force is softened already at distances smaller than 2.8 times the softening length (which is defined as the Plummer equivalent softening) as opposed to only 2 softening lengths with the spline kernel. Therefore we rescaled the softening length in GIZMO to 70 pc, in order to have the same spatial resolution for gravity of GASOLINE/GASOLINE2 which employ a spline or Wedland kernel. Finally, we implement the same pressure floor as in GASOLINE2, albeit the actual definition differs owing to the different definition of the kernel size h (which is twice that in GASOLINE2). In GIZMO we compute radiative cooling using GRACKLE [6] a chemistry and cooling library (Bryan et al. 2014; Kim et al. 2014).

In GASOLINE/GASOLINE2 and GIZMO star formation is implemented via a stochastic prescription based on the Schmidt law (Kennicutt 1998), using the same criteria as described in Stinson et al. (2006). Since we are unable to resolve single stars, our stellar particles are assumed to represent an entire stellar population with its age, metallicity and a Chabrier IMF Chabrier 2003). We allow stars to form in regions above a density of 10 atoms/cm^3 and below a temperature of 30.000 K, and adopt a star formation efficiency of 0.01, all as in Tamburello et al. 2015. In all codes we model stellar feedback via type II and type Ia SNe and including also mass loss from low and intermediate mass stars. The time of injection for type II SNe and for the mass loss is computed according to the stellar lifetimes as derived by Hurley et al. (2000), while the rate of type Ia SNe is modelled according to a distribution of delay times scaling at t^{-1} between 0.1 and 10 Gyr (Kim et al. 2014). For each SN we couple 4×10^{50} erg to the gas in the form of purely

[6] http://grackle.readthedocs.org

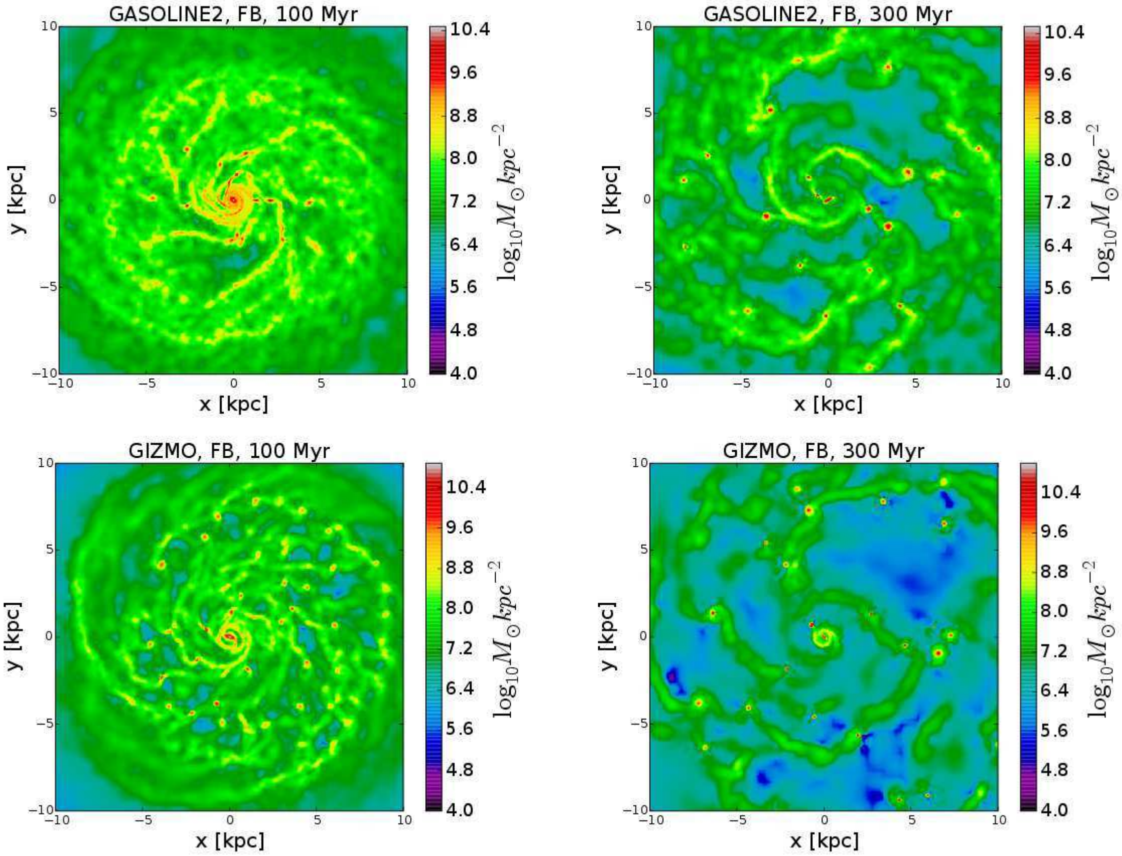

FIG. 1.— Logarithmic color-coded surface density maps of the stellar distribution for the GASOLINE2 (top) and GIZMO runs (bottom) after 100 Myr (left) and 300 Myr (right). Both runs employ blastwave feedback with the same disk initial condition (the relaxed model 11, see text).

thermal energy. In most of our runs we adopt the blastwave sub-grid feedback model (Stinson et al. 2006). In the latter model we temporarily inhibit radiative cooling for gas particles within the SN maximum extension radius $R_{\rm E}$ determined by Chevalier & Gardner (1974) and McKee & Ostriker (1977). The actual time-scale for the cooling shut-off is computed according to the local properties around the stellar particle and amounts to the sum of the duration of the Sedov and snowplaugh phases of the ejecta (see Stinson et al. 2006). For all blastwave feedback runs, with both GASOLINE/GASOLINE2 and GIZMO, we switch-off metal-line cooling because in Tamburello et al. (2015) we found that it has overall little effect but tends to increase fragmentation at lower, poorly resolved scales.

With GASOLINE2 only we also perform runs with the new superbubble feedback implementation, which allows to drive winds without the need of cooling shut-off (Keller et al. 2014). The superbubble feedback model works by depositing thermal energy and ejected mass from SNe into a brief multi-phase state. Multiphase particles each have a pair of separate densities and internal energies, in pressure equilibrium with each other, and for which we calculate separately the cooling rate. Thermal evaporation within multiphase particles converts them back to a single phase typically within a few Myr, and is calculated using classical conduction theory (Cowie & McKee 1977). Resolved hot bubbles then also evaporate their neighbours using a stochastic evaporation model. This model allows SN feedback to deposit energy into a mass determined by physical evaporative mixing, rather than as a purely numerical parameter dependent on resolution. Superbubble allows to achieve efficient self-regulation of star formation in galaxy formation simulations (Keller et al. 2015). In superbubble runs we include also metal-line cooling as its effect on disk stability was not previously explored separately.

4. RESULTS

We evolve the disks with cooling, star formation and feedback turned on for at least 500 Myr after the relaxation phase. If fragmentation occurs it should happen after only 100-200 Myr, namely a few local disk orbital times, as expected for gravitational instability (Gammie 2001; Durisen et al. 2007).

Figure 1 shows the stellar density maps at different times for runs with GASOLINE2 and GIZMO. Fragmentation is slightly more vigorous in the GIZMO runs as opposed to the SPH runs, as shown by the sharper density contrast between the clumps and the surrounding medium at 300 Myr (Figure 1). Clumps in GIZMO also exhibit a more elongated shape. Similar differences have been noted in the past for sub-stellar clumps in fragmenting protoplanetary disks when comparing SPH and grid-based codes (see e.g. Durisen et al. 2007; Mayer & Gawryszczak 2008). Overall, clumps span sizes of a few hundred pc in both codes. When we compare the

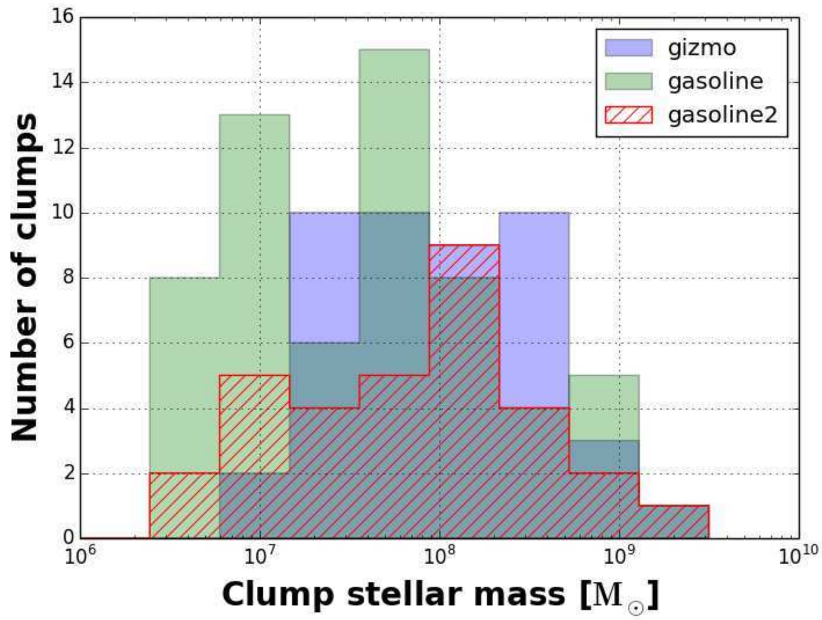

FIG. 2.— Mass function of stellar clumps in GIZMO , GASOLINE and GASOLINE2 massive disk runs with blastwave feedback, obtained by stacking different time snapshots (at 200 and 500 Myr) as in Tamburello et al. 2015.

mass function of clumps identified using the SKID group finder as gravitationally bound objects, the three simulations yield similar results (Figure 2). In particular in the GIZMO and GASOLINE2 runs the mass function obtained by stacking different time snapshots (see Tamburello et al. 2015) is flatter and has a less prominent low mass tail relative to the GASOLINE run, but the characteristic mass scale where the distribution peaks, between a few times 10^7 M$_\odot$ and $\sim 10^8$ M$_\odot$, is comparable in all three runs. Most importantly the cut-off at $\sim 10^9$ M$_\odot$ is similarly sharp in all cases. These results confirm the findings of Tamburello et al. (2015) as well as their explanation of the characteristic initial fragmentation scale based on Toomre-unstable patches in corotation (see also Boley et al. 2010). The more numerous clumps below 10^6 M$_\odot$ seen in the GASOLINE run are likely the result of numerical surface tension in standard SPH stifling mixing in regions with high density contrast. We conclude that, for a given choice of feedback model, results on fragmentation and properties of massive clumps are relatively insensitive to the hydro method.

Next we turn to compare GASOLINE2 runs performed with different feedback prescriptions. Figure 4 compares the star formation histories of the blastwave and superbubble feedback runs, highlighting the dramatic ability of superbubble to suppress star formation efficiently. There is a factor of several lower star formation after the initial burst in superbubble. This difference reflects the ability of superbubble to match naturally the stellar mass to halo mass relation at all redshifts in cosmological simulations (Keller et al. 2015).

The suppression of star formation results from efficient supernovae heating of the gas. Heating acts to stabilize the disk against self-gravity, thereby leading to a radically different result compared to blastwave feedback runs (Figure 4). Transient overdensities do appear only in the first 200 Myr, but disappear in less than an orbit. The lower panel of Figure 4 shows our attempt to verify the strong suppression of fragmentation by superbubble using the more extreme disk model with 80% gas mass. This also does not result in long-lasting clumps.

We tested that if we reduce the strength of the initial burst by increasing gradually the star formation efficiency the result does not change, namely the disk still does not give rise to giant clumps with superbubble feedback.

A limitation of these simulations is of course that they adopt isolated disks, which are neither accreting gas nor can be perturbed by external galaxies. Both effects are ubiquitous at high-redshift (e.g. Agertz et al. 2009; Mandelker et al. 2015). Tidal perturbations might drive disk instability and promote fragmentation in disks that would be stable in isolation. In order to test this hypothesis we design a new initial condition in which a massive satellite, with virial mass one fifth of that of the primary galaxy, is launched on a plunging orbit towards the primary. We use the default disk model 11 for the primary galaxy, and run the simulations with superbubble feedback only since we want to test how sensitive is the no-fragmentation result to the specific dynamical configuration. We represent the satellite with a softened massive particle having a mass half of its virial mass (to account for tidal truncation) and a gravitational softening equal to its half mass radius (radii and masses are scaled from the primary virial mass and virial radius using standard scaling laws for CDM halos, see eg Tamburello et al. 2015).

We run two simulations with the satellite placed on two different orbits, one on an eccentric orbit with apocenter-to-pericenter ratio of 5:1 (the pericenter is about 2 kpc), typical of cosmological substructures, and one on a circular orbit (with a radius of 9 kpc, hence grazing the outer

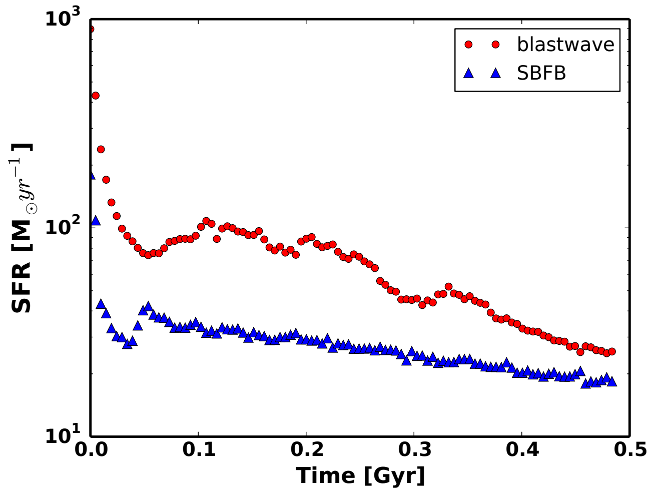

FIG. 3.— Comparison of the star formation histories of model 11 run with GASOLINE2 using blastwave feedback (red dots) and superbubble feedback (blue triangles). The stronger suppression of star formation by superbubble feedback is clearly evident

disk). The simulations show that mild fragmentation is triggered in the heavily perturbed outer disk of the primary, although it gives rise to only a couple of transient clumps that last less than 50 Myr. Interestingly, this time scale is comparable to that found by the FIRE cosmological simulations group (Oklopcic et al. 2016). In the eccentric orbit simulation two clumps appear after about 190 Myr, the most significant of which encompasses $\sim 2\times10^8$ M$_\odot$ of gas and about 1.7×10^8 M$_\odot$ in stars, and is located in the tidal arm forced by the satellite in the primary galaxy (Figure 5). It is more prominent in the gas distribution than in the stellar density maps (Figure 5). Like this one, all the other triggered clumps are located far from the centre of the galaxy, at more than 5 kpc, and are dominated by gas. Their rapid dissolution is due to the fact that they are loosely bound, hence easily torn apart by differential rotation as they migrate towards the inner region of the main galaxy host. This is in good agreement with the results of Oklopcic et al. (2016), who found nearly all their clumps to be far from virialization.

5. DISCUSSION AND SUMMARY

We have presented novel results from a set of simulations employing both different hydrodynamical codes and different feedback models to scrutinize the popular notion that a significant fraction of observed high-z star forming clumps comes from the fragmentation of massive star-forming gas disks. We found that fragmentation, including clump properties, is rather insensitive to the detail of the hydrodynamical technique adopted, while it is strongly sensitive to the feedback model adopted. In particular, we used a new feedback model that, as some of the other recent feedback models introduced in the galaxy formation literature, is designed to allow an effective, resolution-independent generation of supernovae outflows, establishing efficient self-regulation of star formation and allowing to reproduce naturally the stellar mass-to-halo mass relation from high to low redshift. The result is striking as disk fragmentation is completely suppressed for isolated disk and only marginally possible, in the form of transient overdensities, in disks perturbed by massive satellites. The same disks fragment copiously, producing some clumps with masses in excess of 10^8 M$_\odot$, when a less efficient feedback model is adopted, for both GASOLINE2 and GIZMO. Such feedback model, however, is known to overproduce stellar masses by a factor of 2 or more at $z>0$ for galaxies at the mass scale of the Milky Way and above (e.g. Fiacconi et al. 2015).

We argue that our results underscore a new important tension in our understanding of galaxy formation. Violent gravitational instability of galactic disks appears to be at odds with the picture of efficient self-regulation of galaxy assembly by feedback. Different solutions can be envisioned. First, it may well be that the outcome we obtain with superbubble is the correct one, and that the majority of massive star forming clumps have an "ex-situ" origin , for example as cores of massive satellites (in multiple minor mergers, which should be common at high-z for massive galaxies at the peak of their growth) or from fragmentation of a different nature, such as induced by thermal instabilities in cold flows feeding the galaxies. Perturbations by massive satellites would also be instrumental to trigger some "in-situ" clump formation, as shown by our superbubble runs with a perturber and as hinted also by the analysis of Oklopcic et al. (2016), who showed that the most prominent clumpy phases correspond to times at which perturbations by satellites occur. Second, our results might indicate that we are still failing to understand the way feedback works, or at least how it works at galactic noon, namely at $z\sim2$, when massive, gas-rich star forming disks are in place and are at the peak of their growth. Indeed, the same standard blastwave feedback that overproduces stellar masses at high z (Fiacconi et al. 2015) does produce stellar masses that do match observational constraints at low redshift (Guedes et al. 2011; Sokołowska et al. 2016). Incidentally, work has illustrated how fundamental aspects of feedback, such as the momentum budget injected in the gas by multiple SNe, has not been correctly predicted so far, suggesting that the rationale behind the latest generation of feedback models may have to be revised (Gentry et al. 2016).

In either case star forming massive clumps appear to

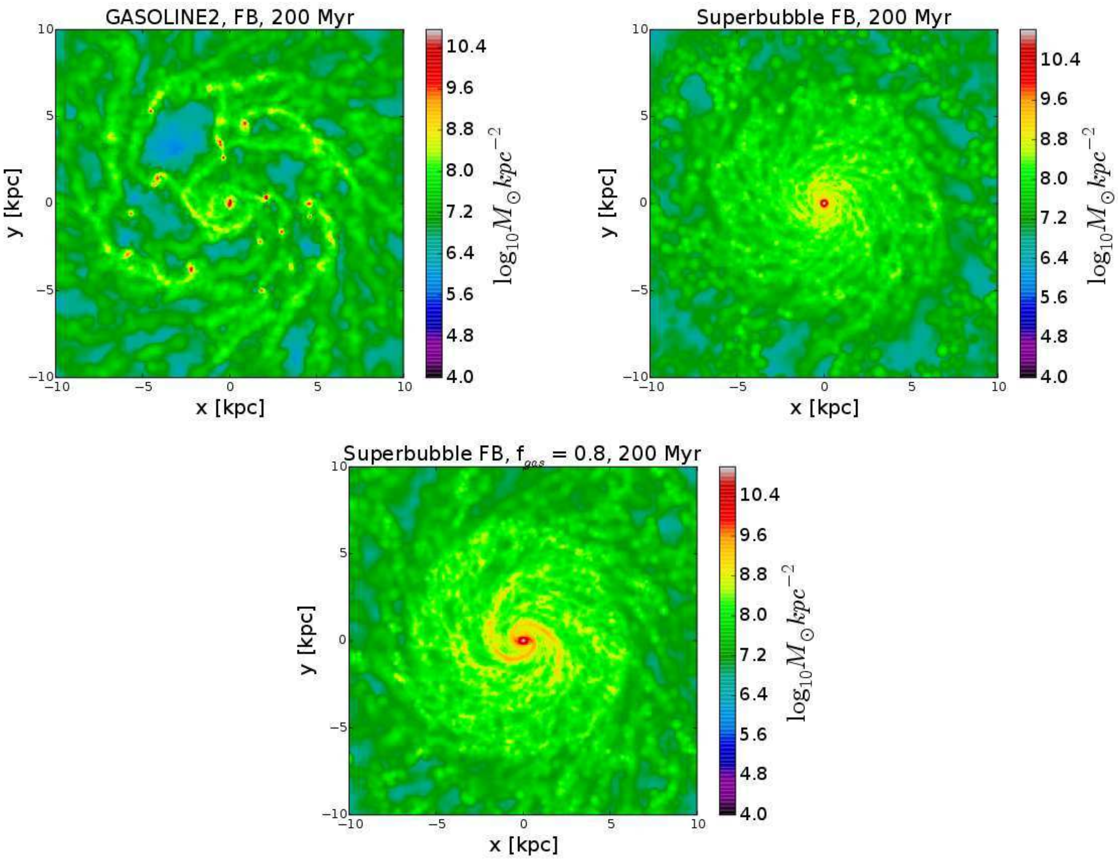

FIG. 4.— Comparison between the logarithmic stellar surface density maps for the default galaxy model 11 run with GASOLINE2 using blastwave feedback (left) and superbubble feedback (middle) at 200 Myr. The model with gas fraction increased to 80%, also run with superbubble feedback, is shown in the bottom panel at 200 Myr.

be a new important testbed of our feedback processes in galaxy formation. Unambiguous evidence of the fragmentation scenario for high-z star forming clumps will probably come only from direct observations of the cold gas phase, since fragmentation starts there in the first place and should leave its imprint on the dynamics of the gas disk, for example in the form of large-scale turbulent motions (Agertz et al. 2009b). Hence future observations of the distribution and kinematics of cold neutral hydrogen and molecular gas in $z > 1$ massive galaxies may provide the crucial test.

We have considered only two feedback models in this paper. Yet we believe they represent well two markedly different feedback modes widely employed in the literature. In particular, incarnations of the first one, blastwave feedback, have appeared in many of the major hydro codes adopted in galaxy formation, from SPH to AMR (Kim et al. 2014). Likewise, the second one, superbubble, well represents the latest generation of feedback models that can achieve naturally self-regulation of star formation at the desired level, yielding realistic stellar masses as a function of redshift. This is done by generating efficient heating of the gas that reaches temperatures typically $> 10^7$ K as opposed to below that in delayed cooling models. More complex feedback models that achieve the same result but rely on multiple feedback processes, including trapping of infrared radiation from dust heated by UV to generate significant radiation pressure, as in the FIRE model (Hopkins et al. 2014), still generate hot outflows as superbubble. The presumably comparable heating efficiency should lead to a similar stabilization of the disk as observed here. Indeed the properties of the clumps in the FIRE simulations, especially the lack of virialization and short lifetimes, appear very similar to those in our superbubble runs. As already argued in Tamburello et al. 2015, clumps, if they comprise little mass and are transients,are bound to play a negligible role in galaxy evolution, and in particular in the growth of bulges.

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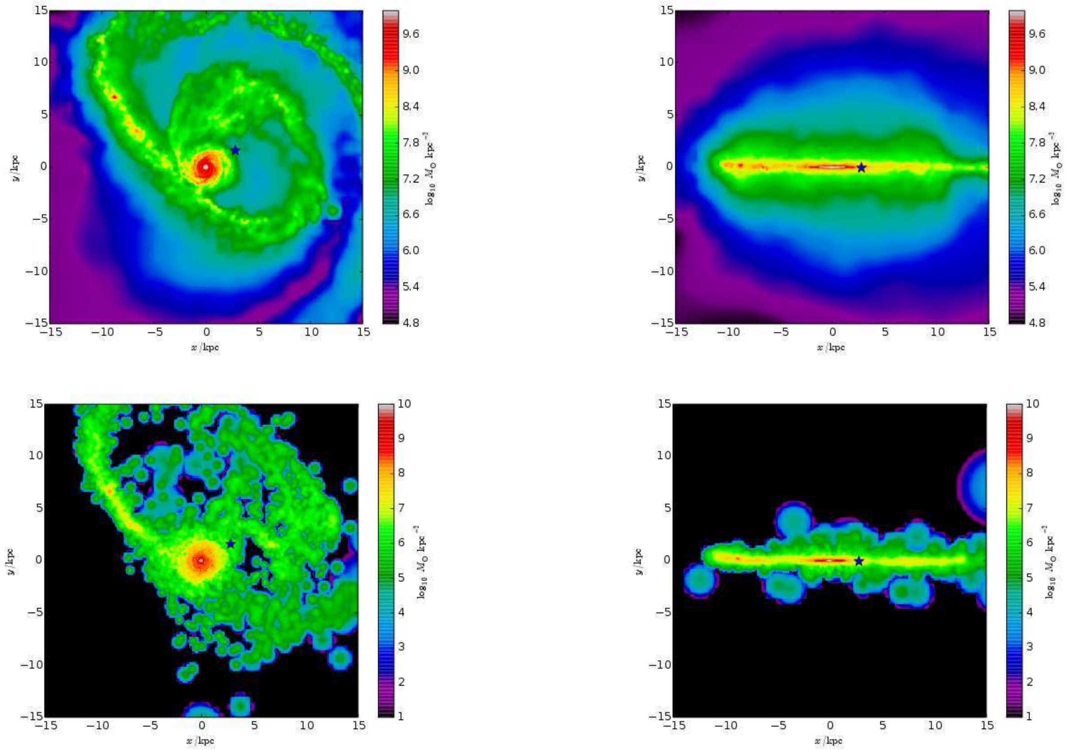

Fig. 5.— Gas (top) and stellar surface density (bottom, showing only the young stars forming during the simulation), both face-on and edge-on, of the superbubble feedback GASOLINE2 run in which model 11 is perturbed by a massive companion on a eccentric orbit (see text). A snapshot after 190 Myr is shown, about 10 Myr after the formation of the transient clumps, which can be seen in the upper left corner of the density maps along the tidally induced arm. The starred point represents the location of the massive satellite.

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